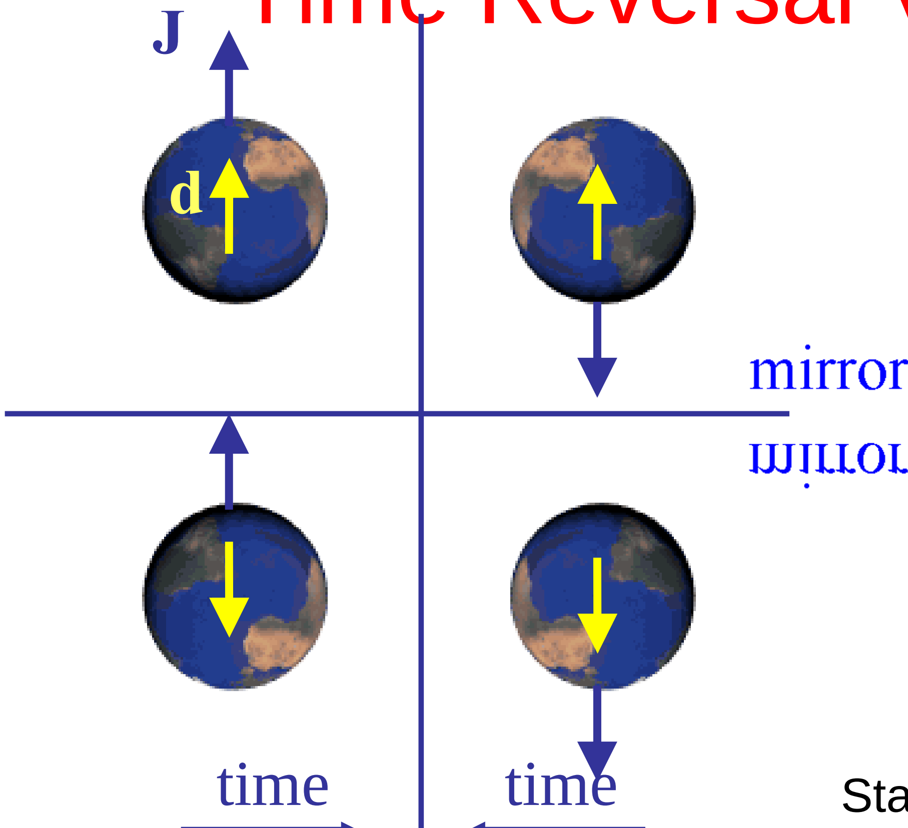
TRIμP: atomic traps for the study of fundamental interactions and symmetries

Radioactive Isotopes in Atom Traps

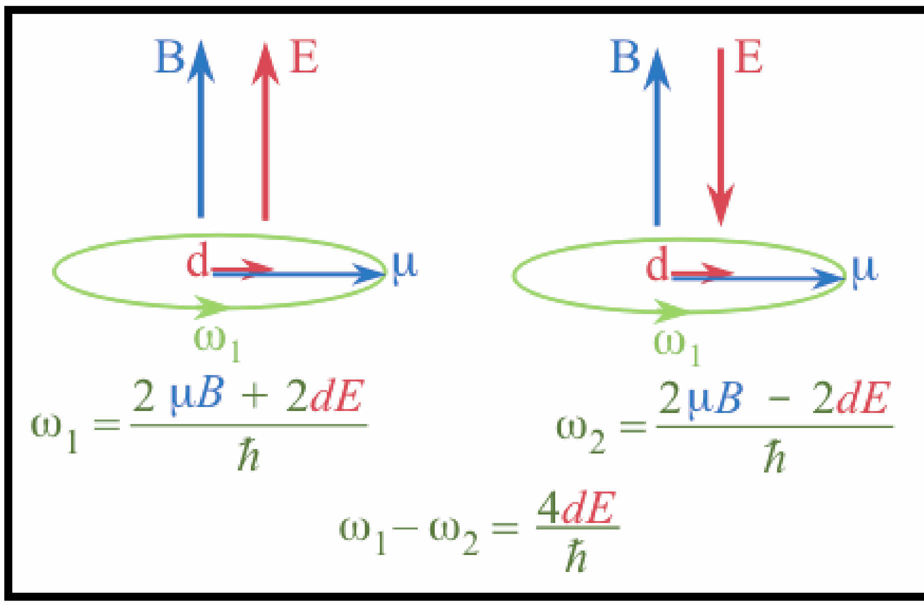
H.W. Wilschut for the TRIμP group

- Electric dipole moments
  - Role of traps
  - Why radioactive isotopes
- Trapping and production
- Weak decays
  - ^{21}Na β decay
- Barium and Radium trapping

Electric Dipole Moment:
Time Reversal Violation (TRV)



Electric dipole moment (EDM)
violates parity and time reversal

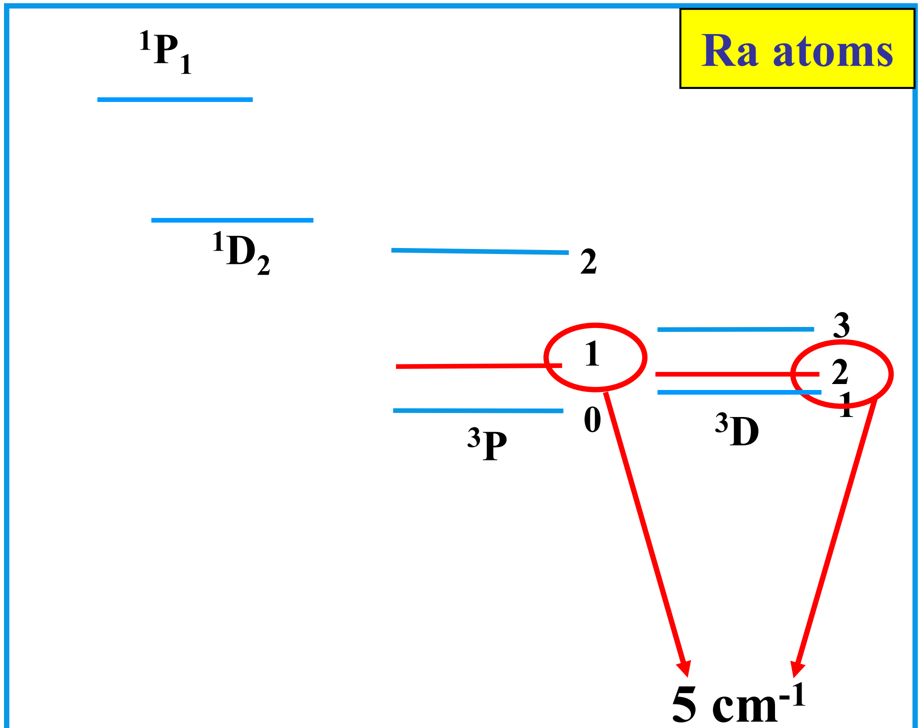


Standard Model: CP and T present in heavy fundamental particles (Kaons, B-mesons). Very strongly suppressed in objects with only u and d quarks

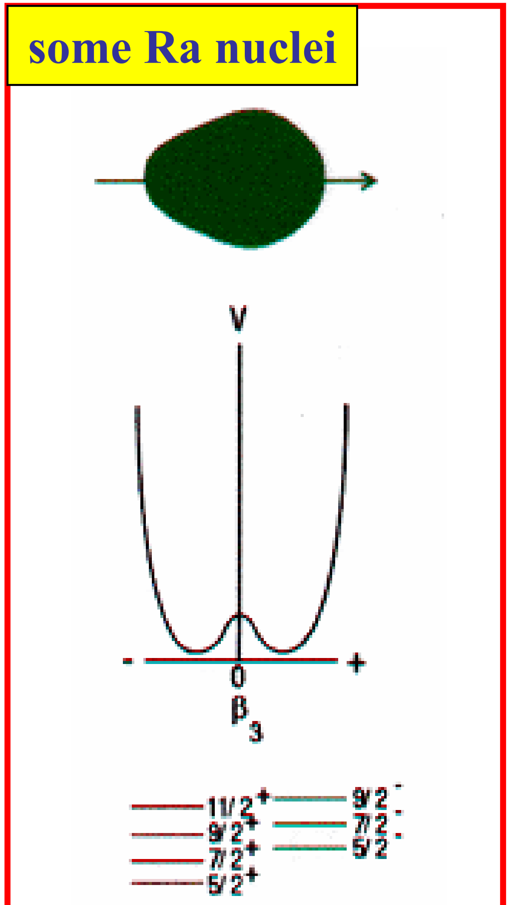
TRV expected: matter/antimatter asymmetry universe…. Supergravity, stringmodels

EDM sensitive to new and expected sources of CP/T violation

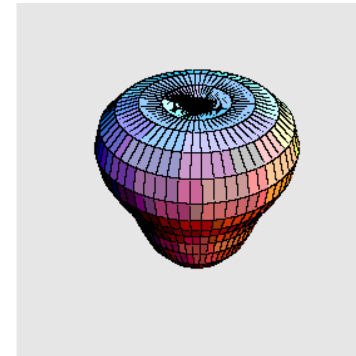
Why radioactive atoms for EDM



$$d = \frac{\langle ^3D_2 | -er | ^3P_1 \rangle \langle ^3P_1 | H_{EDM} | ^3D_2 \rangle}{E(^3D_2) - E(^3P_1)}$$



Nuclei with J=1/2
(213, 225)



Electron EDM enhanced > 10 ^{4}

V. A. Dzuba et al. Phys. Rev. A, 61, 062509 (2000)

Nucleon EDM enhanced ≈ 10^2

J. Engel et al. Phys. Rev. C, 68, 025501 (2003)

Radioactive radium: because of their special properties

Why Trapped Atoms ?

Statistical sensitivity of the EDM measurement

$$\delta d = \frac{\hbar}{4 \varepsilon E \tau \sqrt{N T}}$$

E = Electric field

N = Flux of particles into the measurement region

T = Integration time

τ = Spin coherence time

ε = Efficiency factor

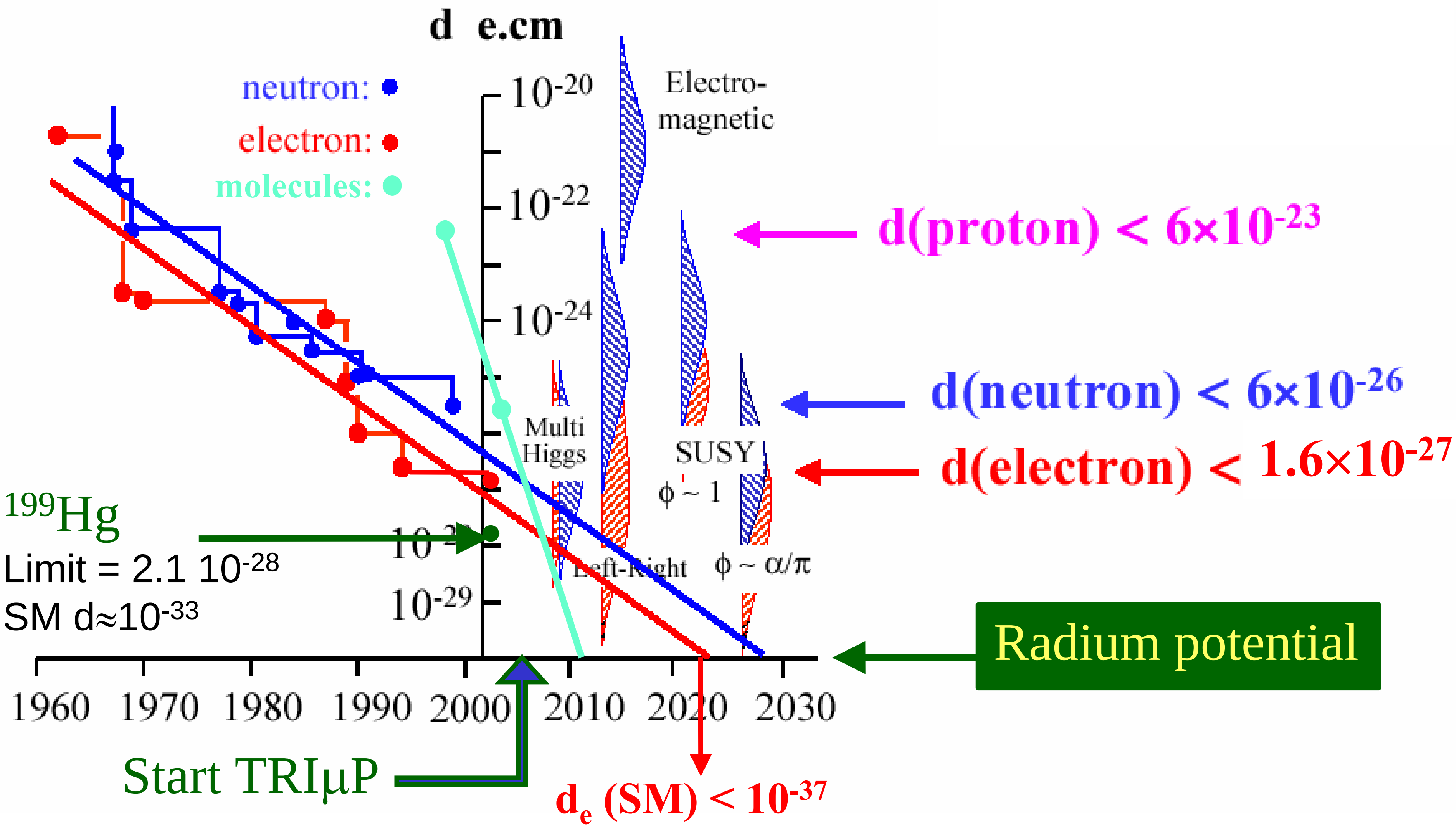
1. **Motion of the particle in the electric field --» magnetic field**

$$\vec{B}_{motional} = \frac{1}{c}\left(\frac{\vec{\mathrm{v}} \times \vec{E}}{c}\right)$$

2. **Smaller sample region in UHV --» $E > 10^5$ V/cm is possible**

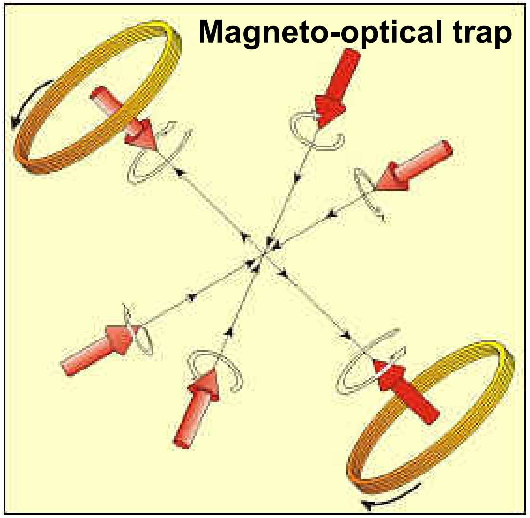
3. **High electric field --» longer spin coherence time ($\tau \sim 100$ s)**

The race for a nonzero EDM…

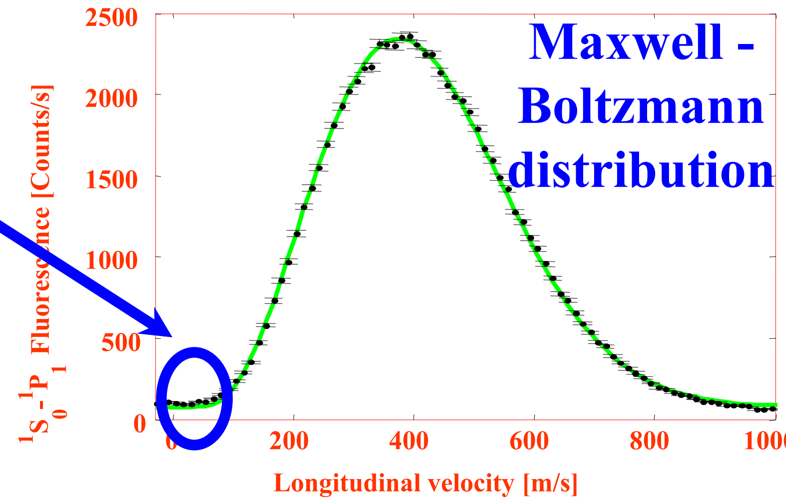


Various particles necessary to resolve origin of TRV

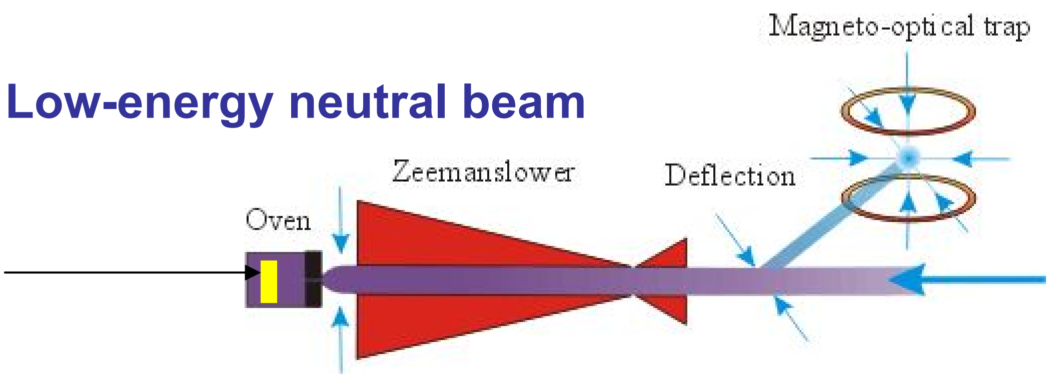
Strategies for trapping radioactive atoms



Useful fraction 0.03%

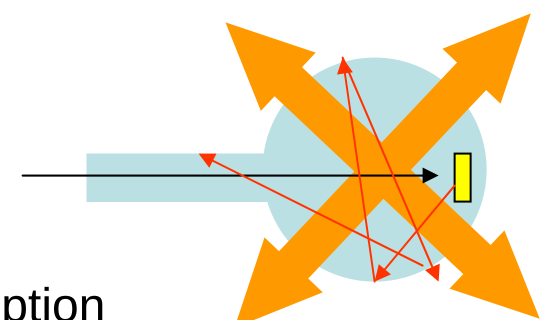


Low-energy neutral beam



options (Zeeman slower not in all cases)
1. Primary beam on target in oven (ISOL)
2. Radioactive beam on stopper in oven
3. Radioactive source in oven

Low-energy radioactive ion beam

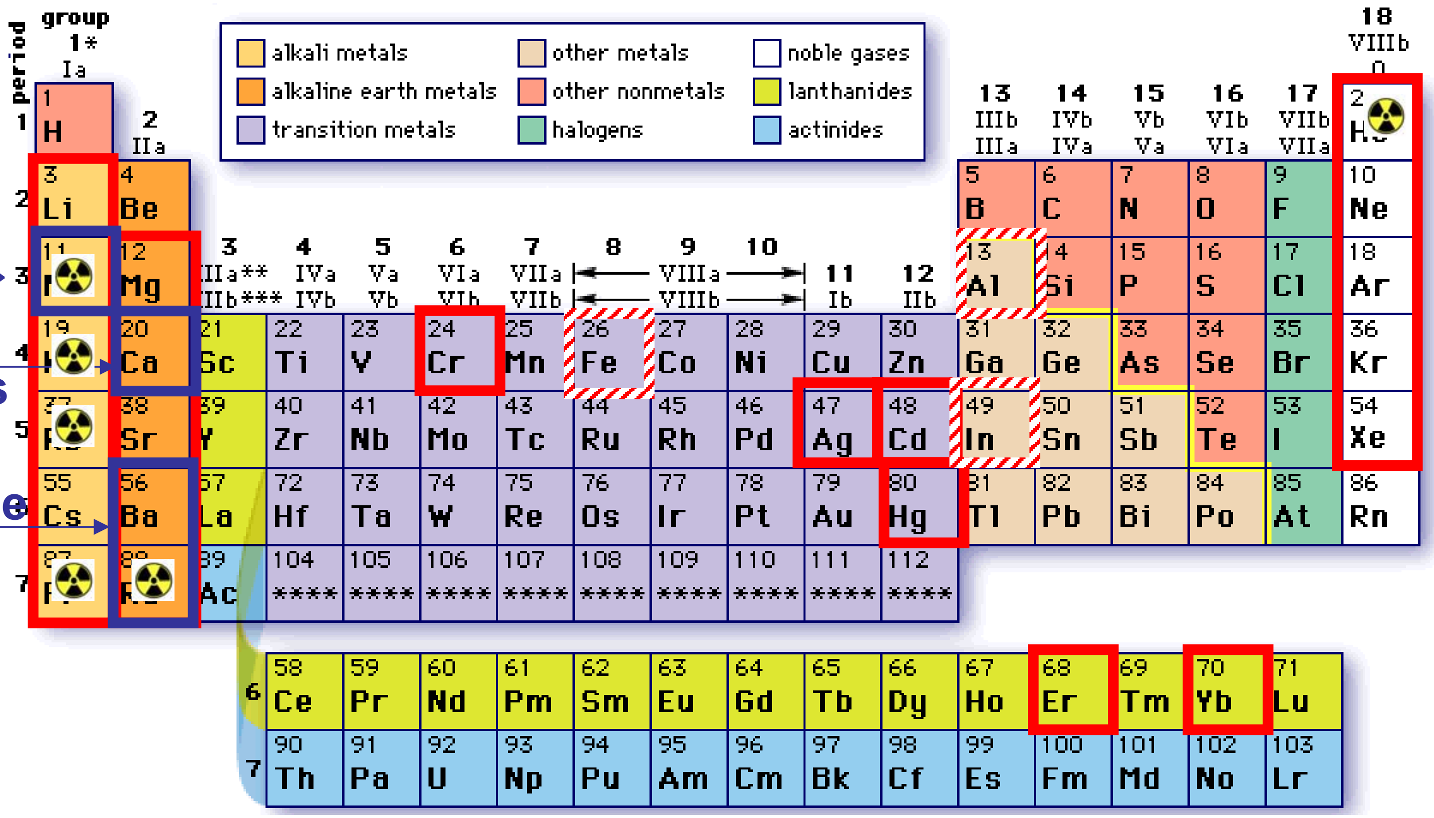


option
multiple pass
$1 - 0.97^n$

Which atoms were trapped in a MOT

KVI:
RIMS
Trace
Analysis

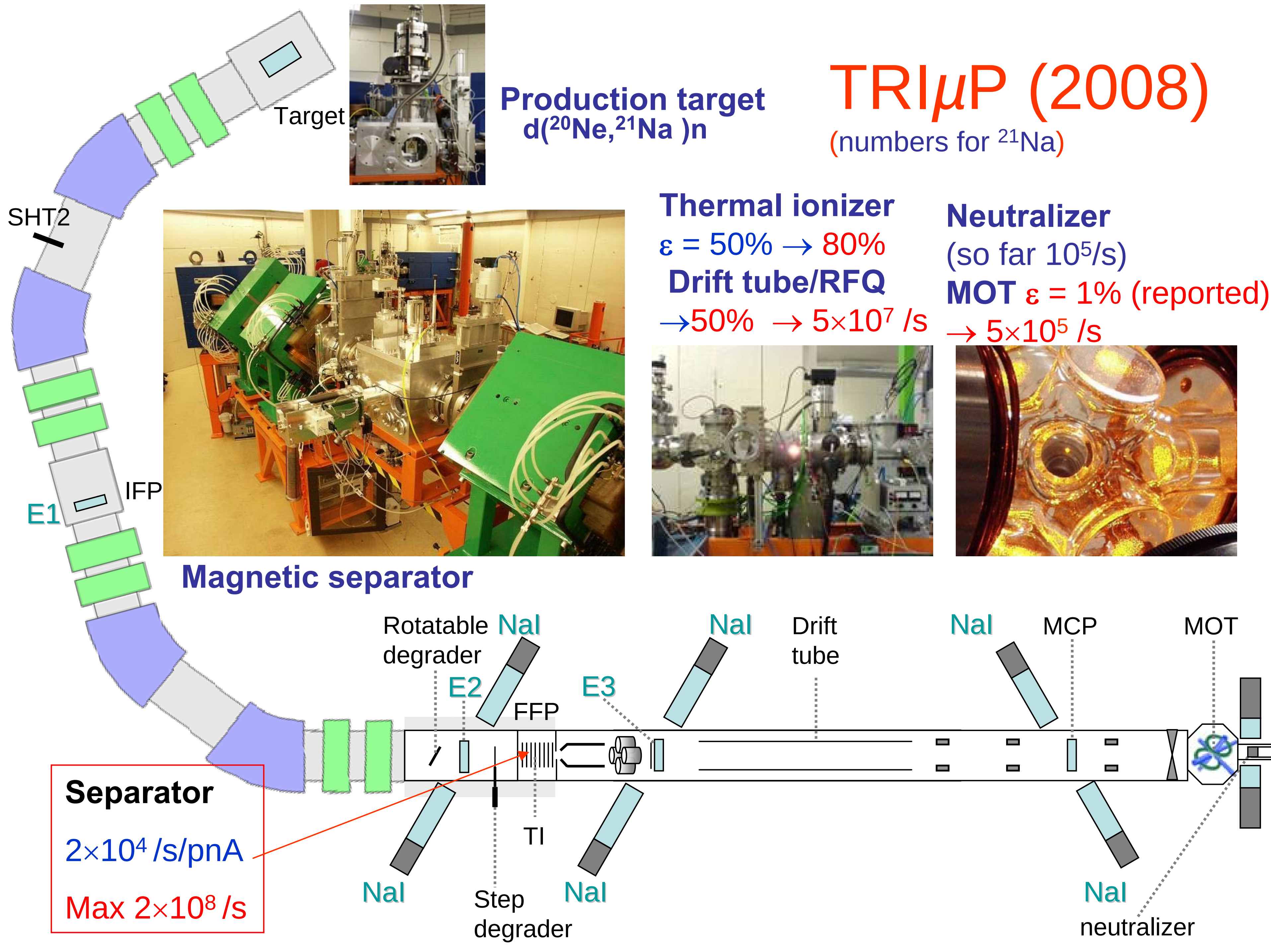
First time



KVI – atomic physics is working with ^{23}Na and $^{(41)}$Ca

KVI – TRIμP Ba trapping as intermediate step for Ra (edm).

KVI – TRIμP pursues ^{21}Na trapping for β-decay correlations

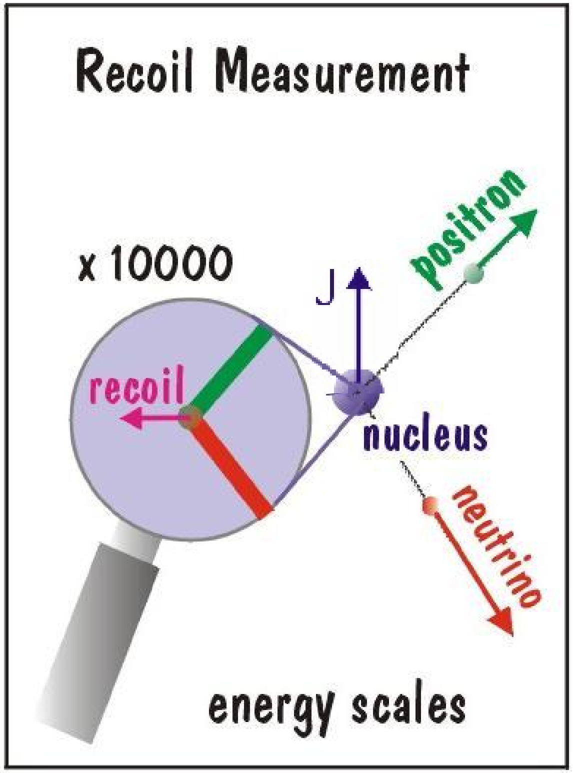

TRIμP (2008)
(numbers for 21Na)
Production target
d(20Ne,21Na)n
Target
SHT2
Thermal ionizer
ε = 50% → 80%
Drift tube/RFQ
→50% → 5×10^7 /s
Neutralizer
(so far 10^5/s)
MOT ε = 1% (reported)
→ 5×10^5 /s
IFP
E1
Magnetic separator
Rotatable degrader
NaI
E2
E3
FFP
Drift tube
MCP
MOT
TI
Step degrader
neutralizer
Separator
2×10^4 /s/pnA
Max 2×10^8 /s

Correlations in β-decay

$$\frac{d^2W}{d\Omega_e d\Omega_\nu} \sim 1 + a\frac{\mathbf{p}\cdot\hat{\mathbf{q}}}{E} + b\Gamma\frac{m_e}{E}$$

$$+ \langle \mathbf{J} \rangle \cdot \left[A\frac{\mathbf{p}}{E} + B\hat{\mathbf{q}} + D\frac{\mathbf{p}\times\hat{\mathbf{q}}}{E} \right]$$

$$+ \langle \boldsymbol{\sigma} \rangle \cdot \left[G\frac{\mathbf{p}}{E} + Q\langle \mathbf{J} \rangle + R\langle \mathbf{J} \rangle \times \frac{\mathbf{p}}{E} \right]$$

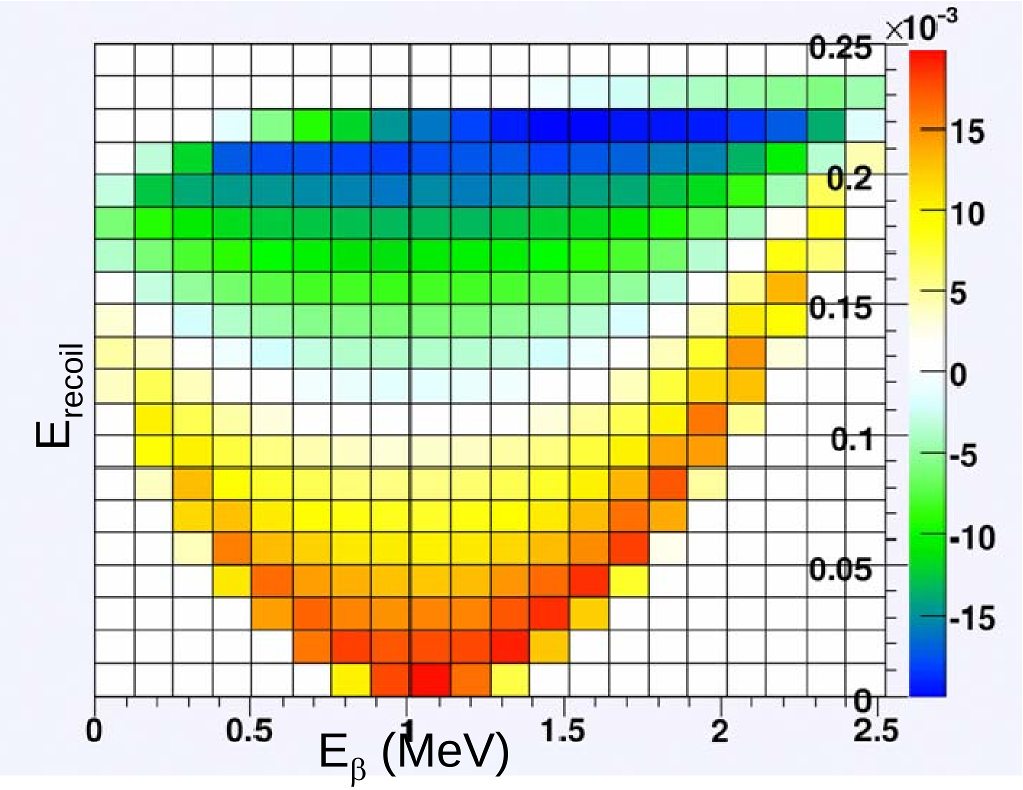


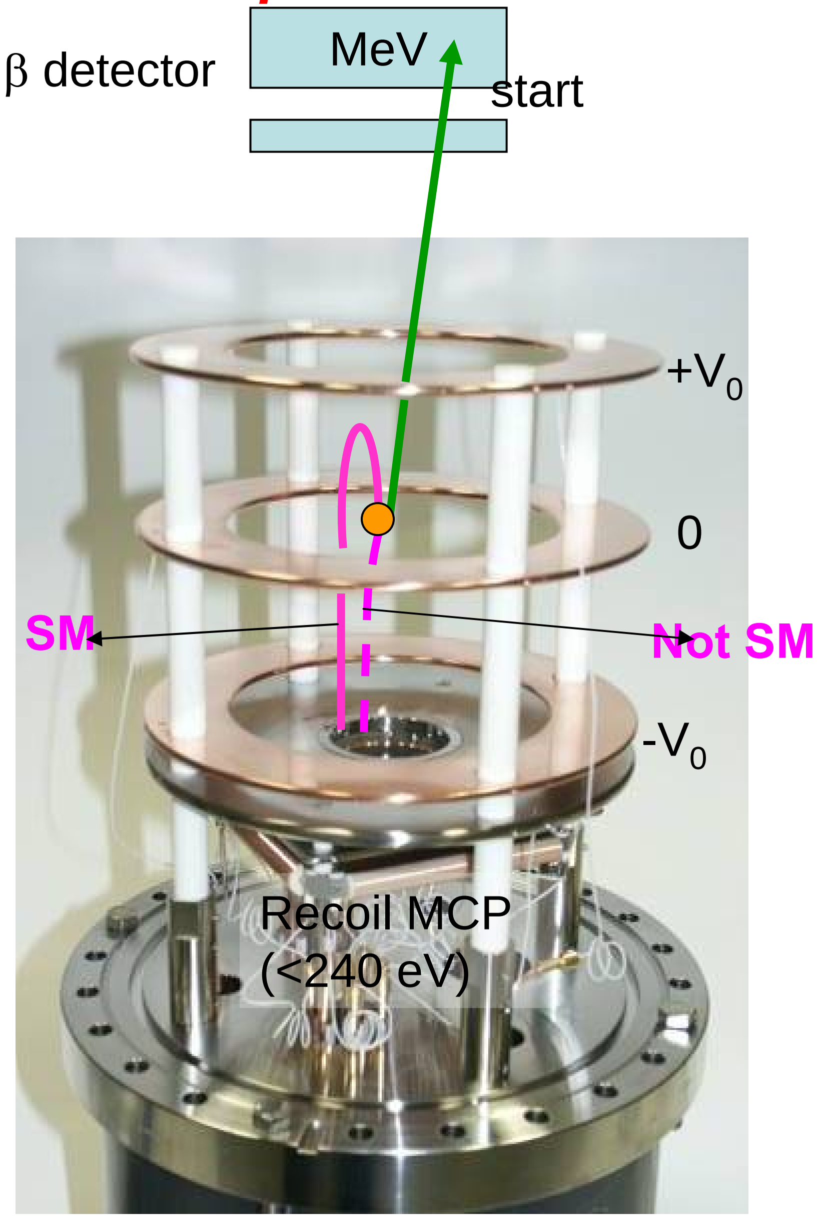
$$E_{recoil} = \frac{(\vec{p}+\vec{q})^2}{2M_{recoil}} < 100\ \mathrm{eV}$$

- Correlation factors *a*…*R* connected by underlying theory
- And with observations outside nuclear β-decay
- Which correlation most potential? (theory input necessary)
- *D* (TRV) as most potential
- In any case:

  must learn the trade with "*a*": ignore spin degrees of freedom

Detection: MOT + RIMS + β detector



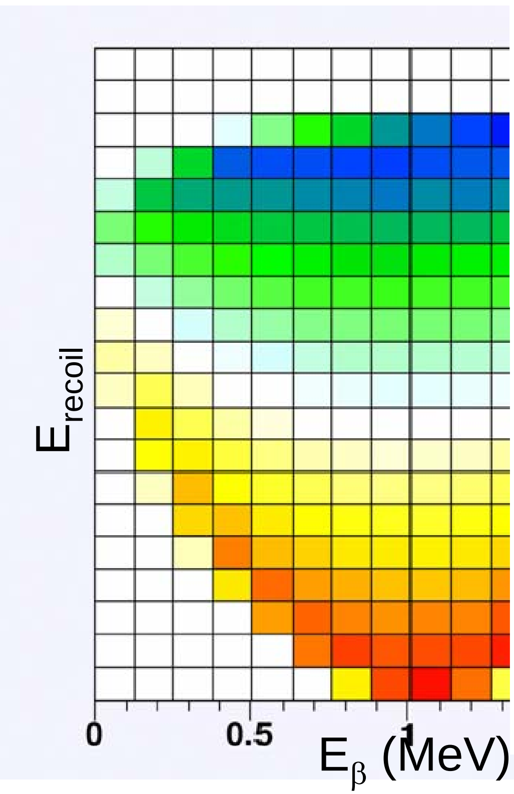


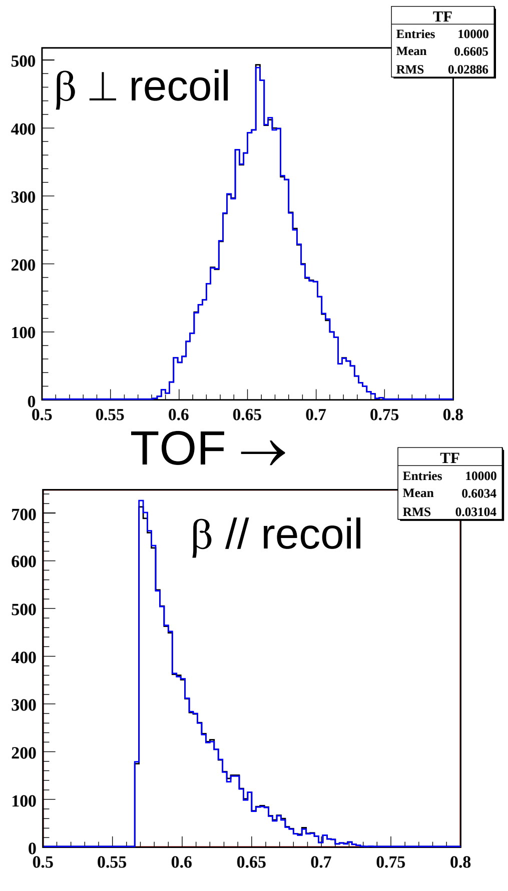
Simulation of 1% change in "a" requires ≥ 10^6 events

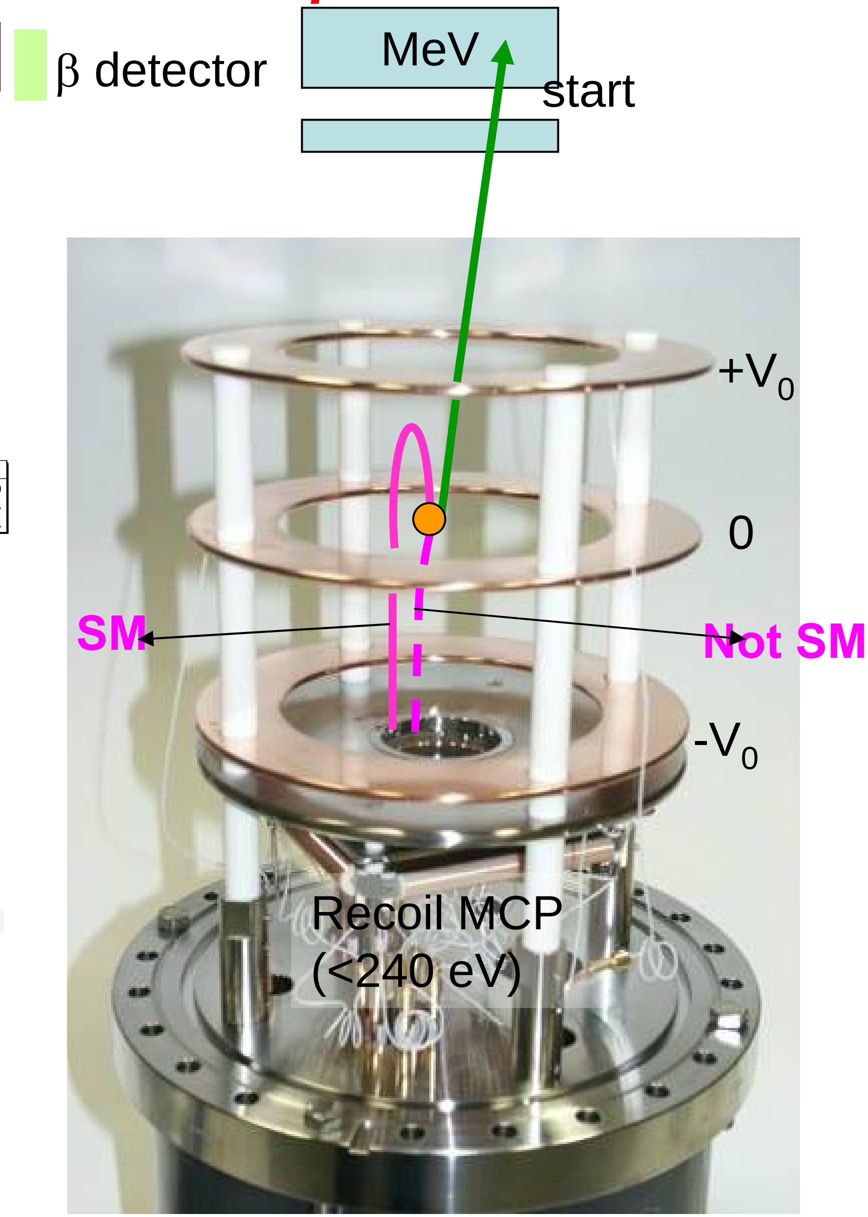
TOF → $E_{//}$

X,Y → $E_{\perp}$

Detection: MOT + RIMS + β detector



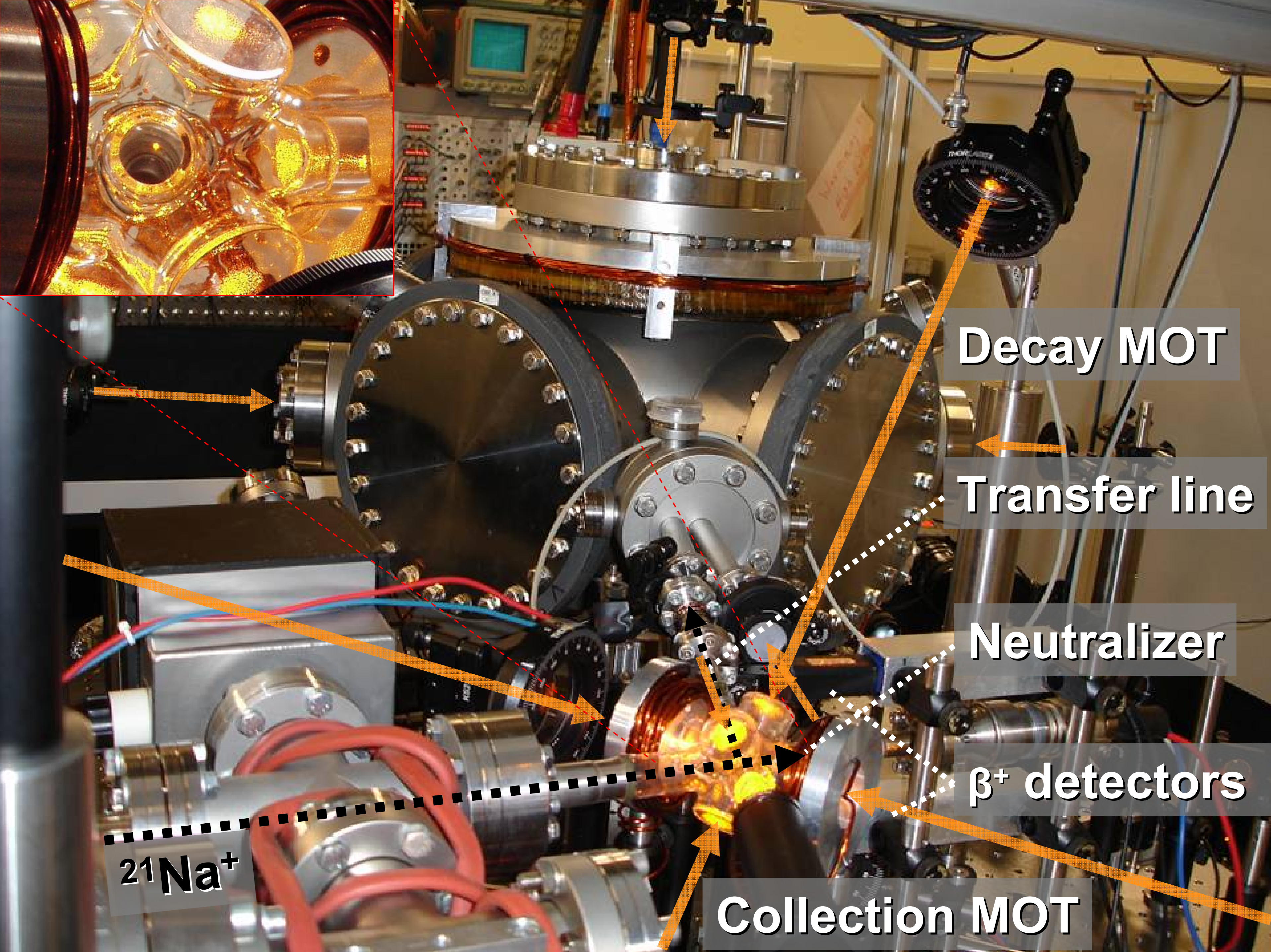


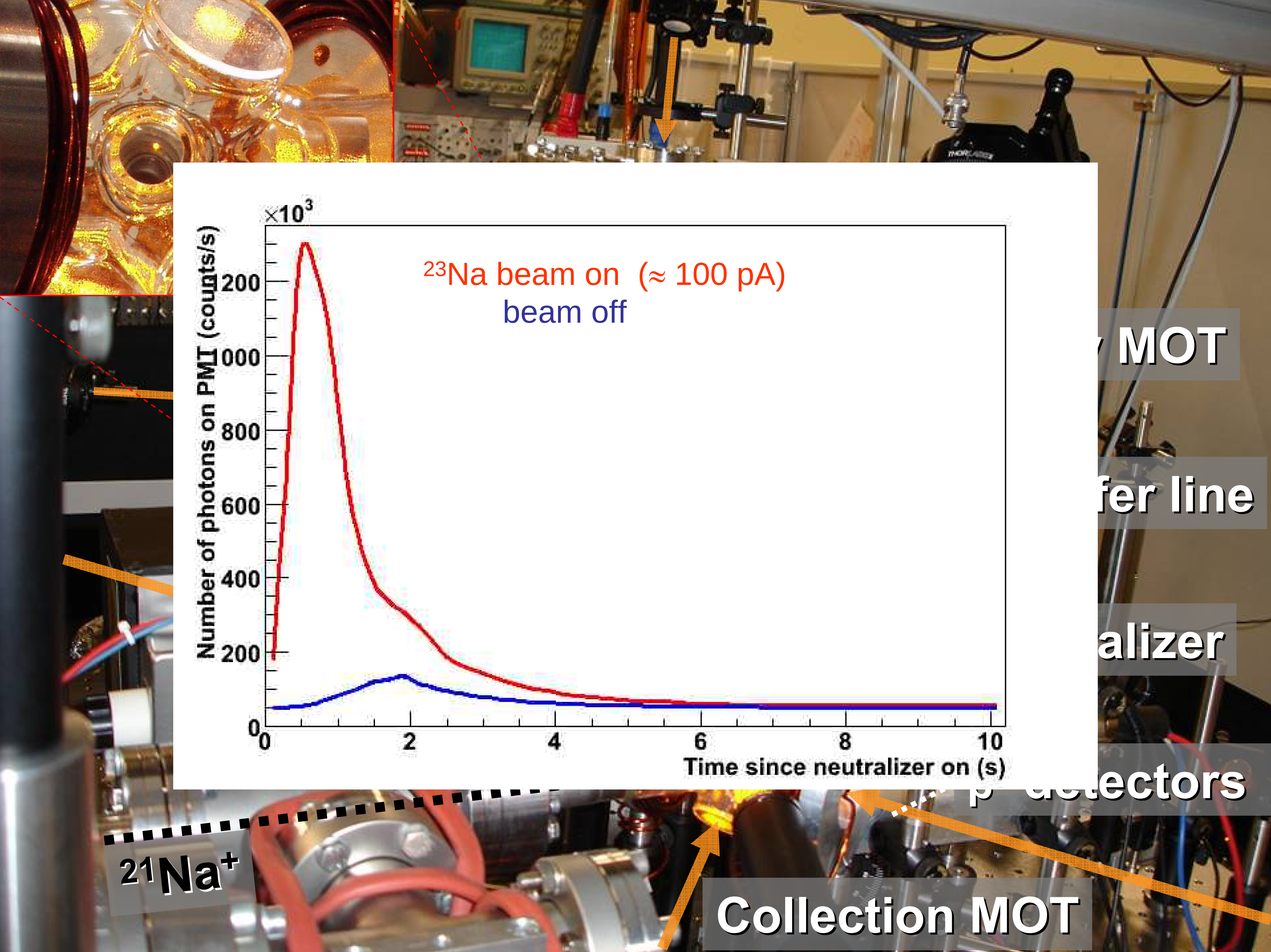


Simulation of 1% change in “a” requires ≥ 10^6 events

TOF→ $E_{//}$

X,Y → $E_{\perp}$


Decay MOT
Transfer line
Neutralizer
β+ detectors
21Na+
Collection MOT


×10³
Number of photons on PMT (counts/s)
1200
1000
800
600
400
200
0
0
2
4
6
8
10
Time since neutralizer on (s)
^{23}Na beam on (≈ 100 pA)
beam off
MOT
^{21}Na^{+}
Collection MOT

Best “a” measurement:

^{38m}K Gorelov et al.

PRL 94(2005)1425

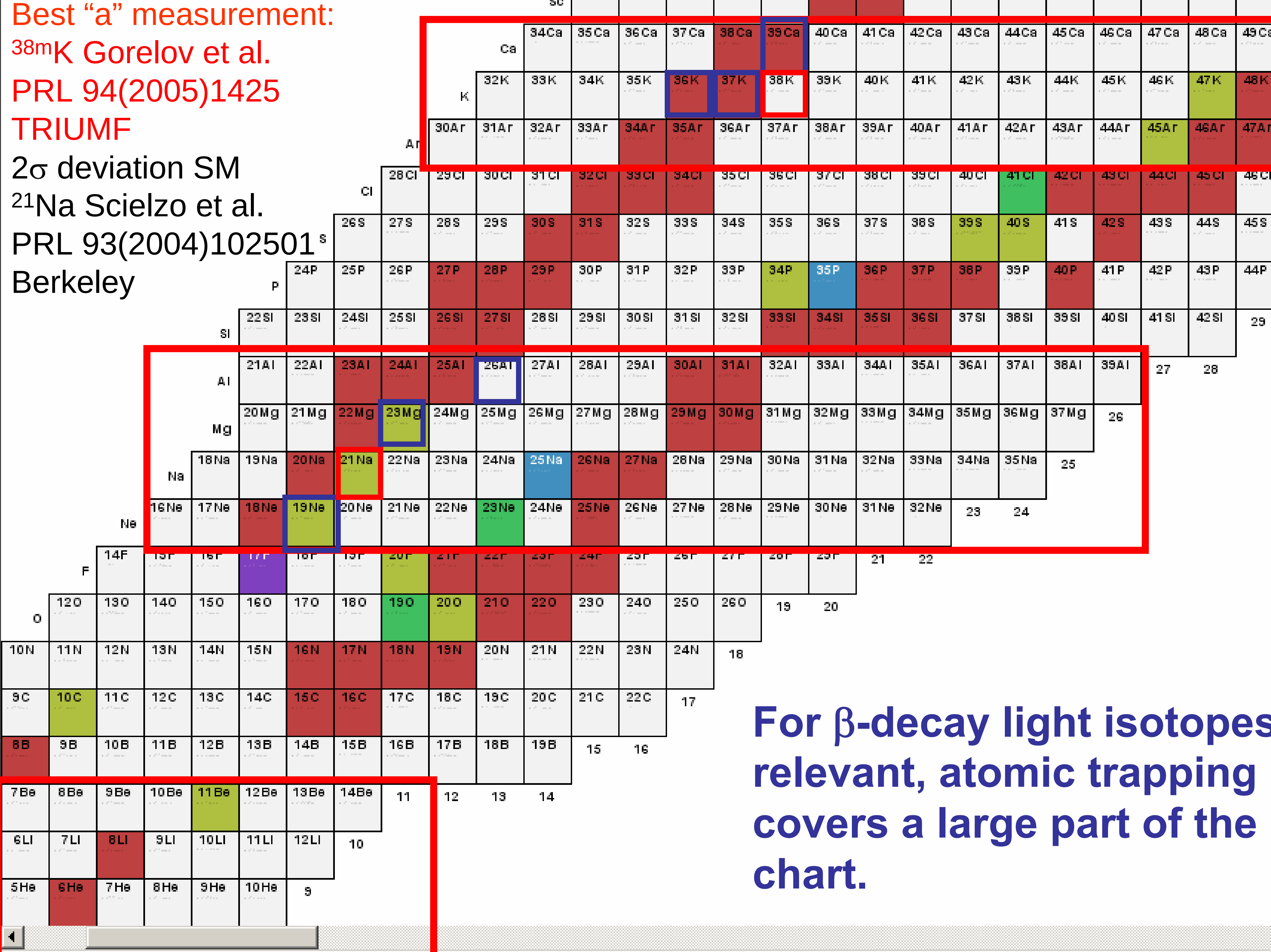
TRIUMF

2σ deviation SM

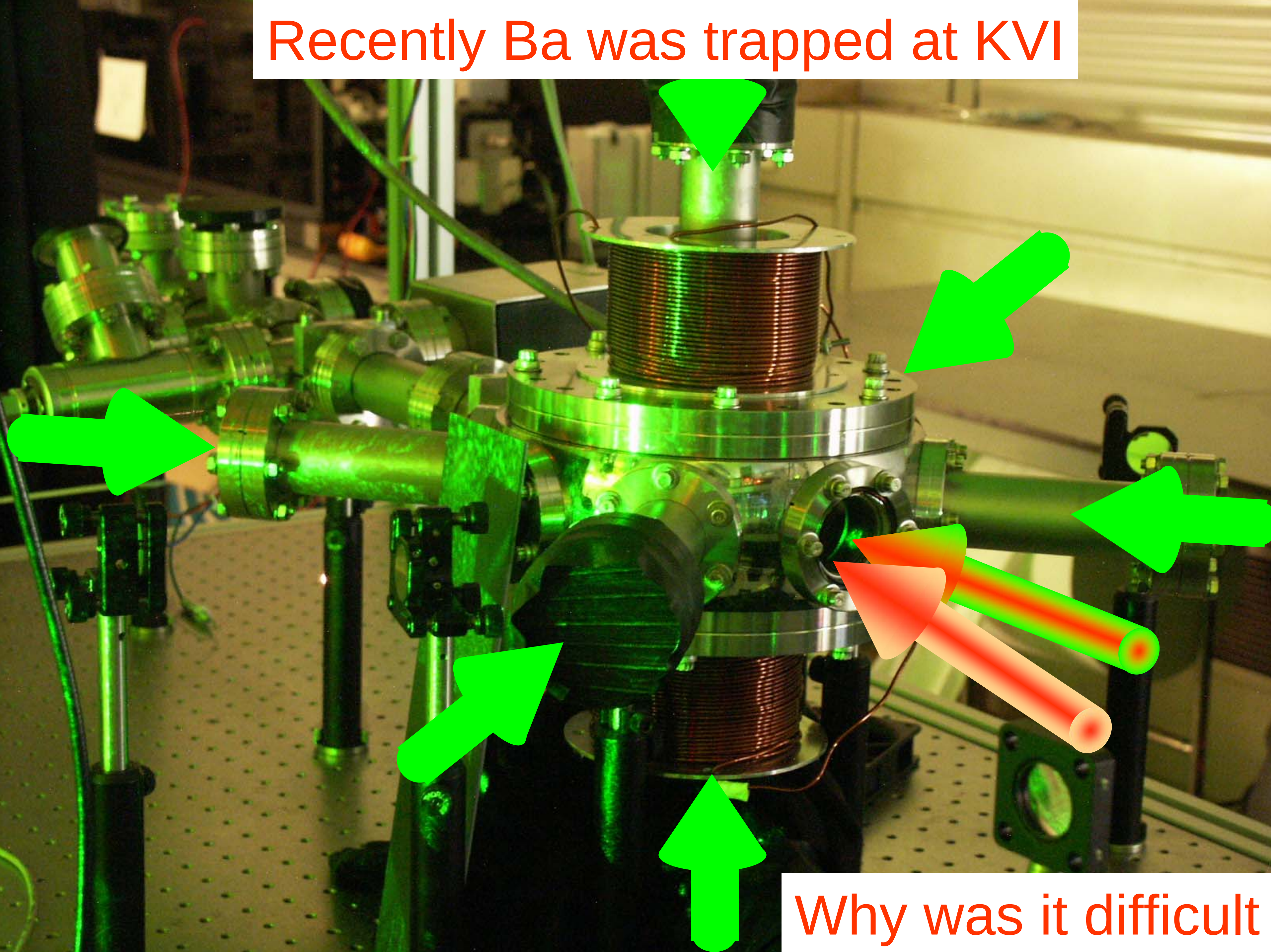
^{21}Na Scielzo et al.

PRL 93(2004)102501

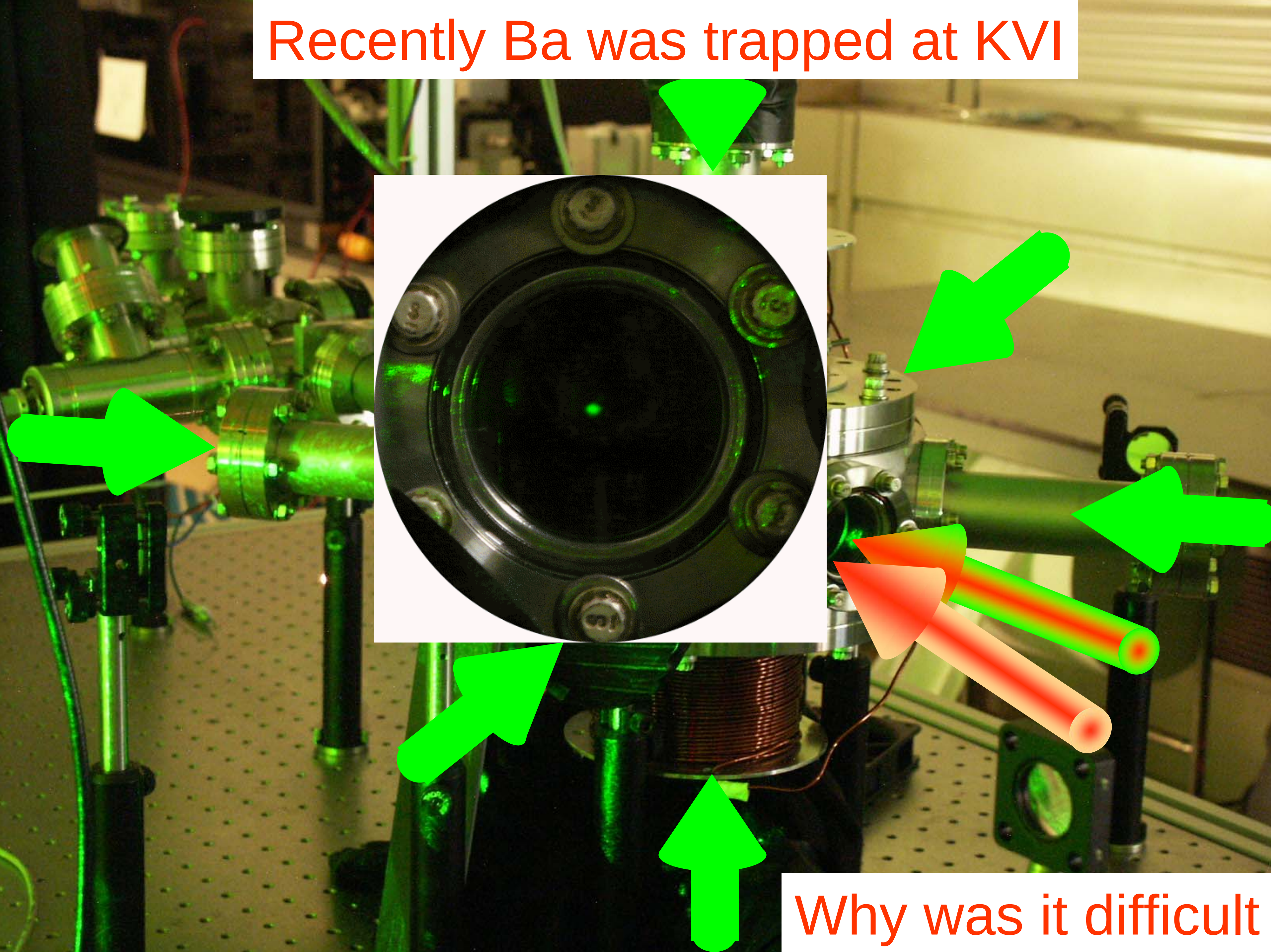
Berkeley



For β-decay light isotopes relevant, atomic trapping covers a large part of the chart.

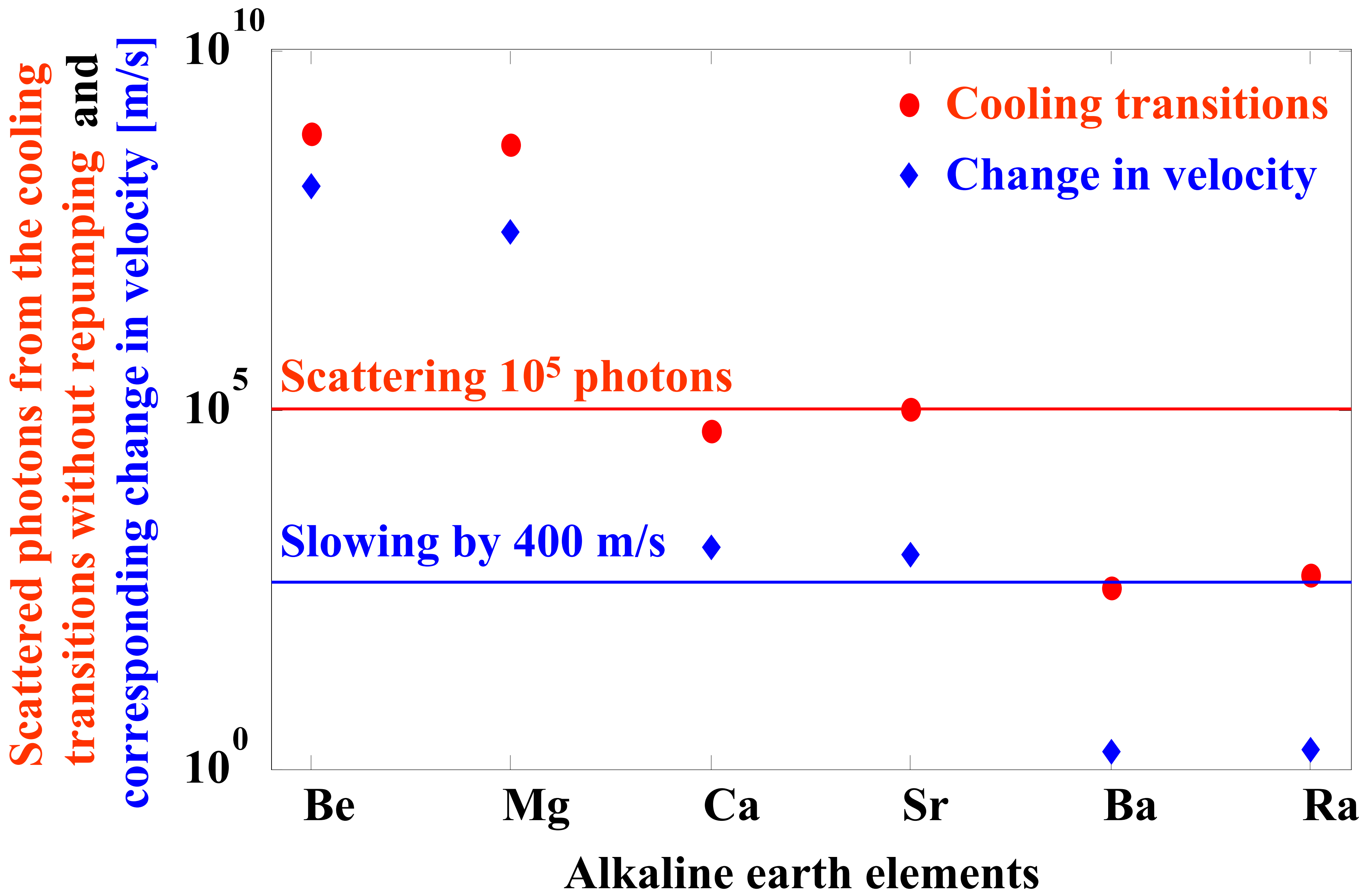

Recently Ba was trapped at KVI
Why was it difficult

Recently Ba was trapped at KVI

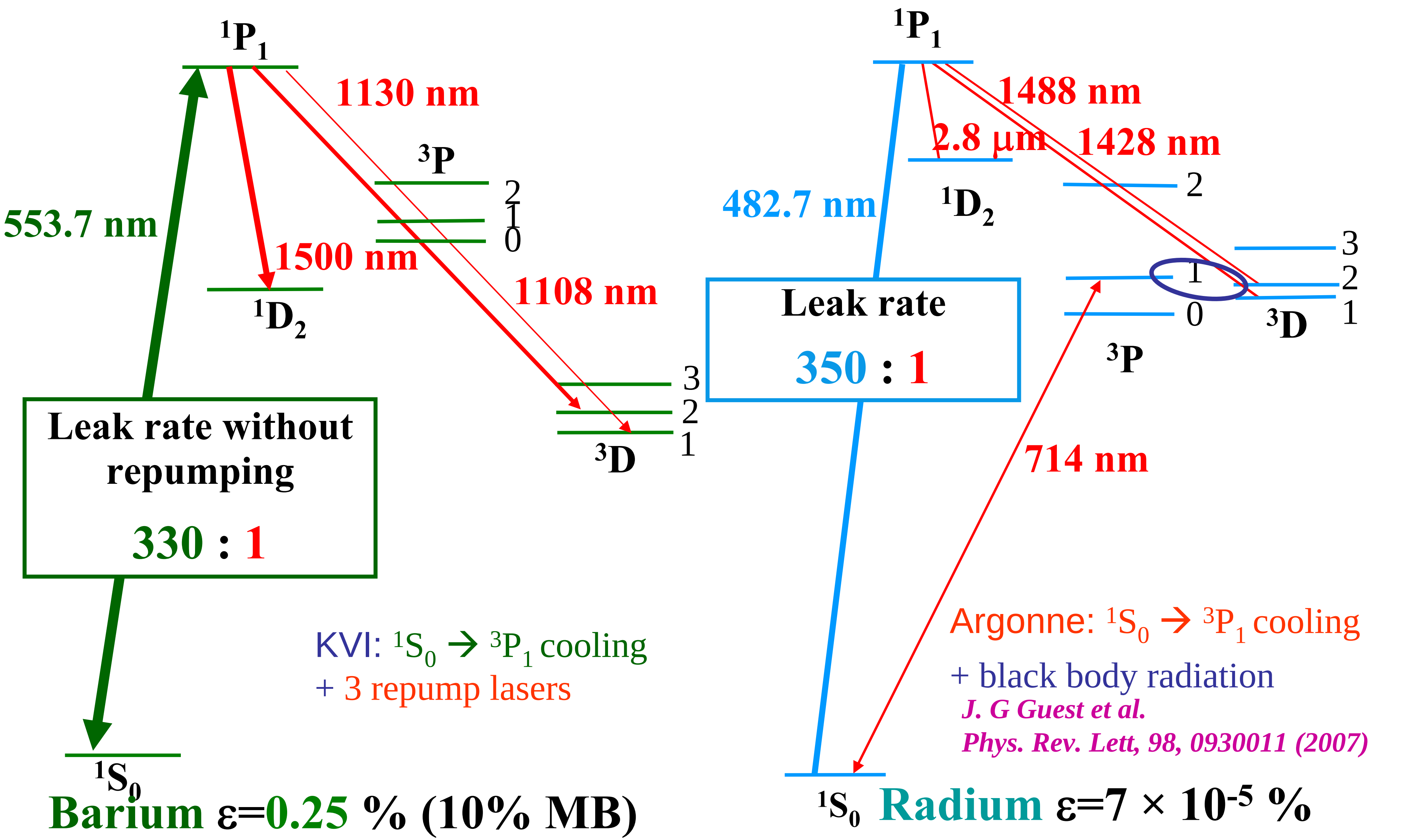


Why was it difficult

Comparison Among All Alkaline-Earth Elements



Laser Cooling of Barium and Radium



TRIμP

Klaus Jungmann
Hans Wilschut
Lorenz Willmann
Gerco Onderwater
(Otto Dermois)

Separator
Emil Traykov (KUL)
Andrey Rogachevskiy

Na
Moslem Sohani
Wilbert Kruithof
Duurt-Jan van der Hoek

Ba/Ra edm
Umakanth Dammalapati
(Glasgow)
Subhadeep De
Aran Mol

Ra ion (APV)
Oscar Versolato
Gouri Giri
Ulrike Guentheria

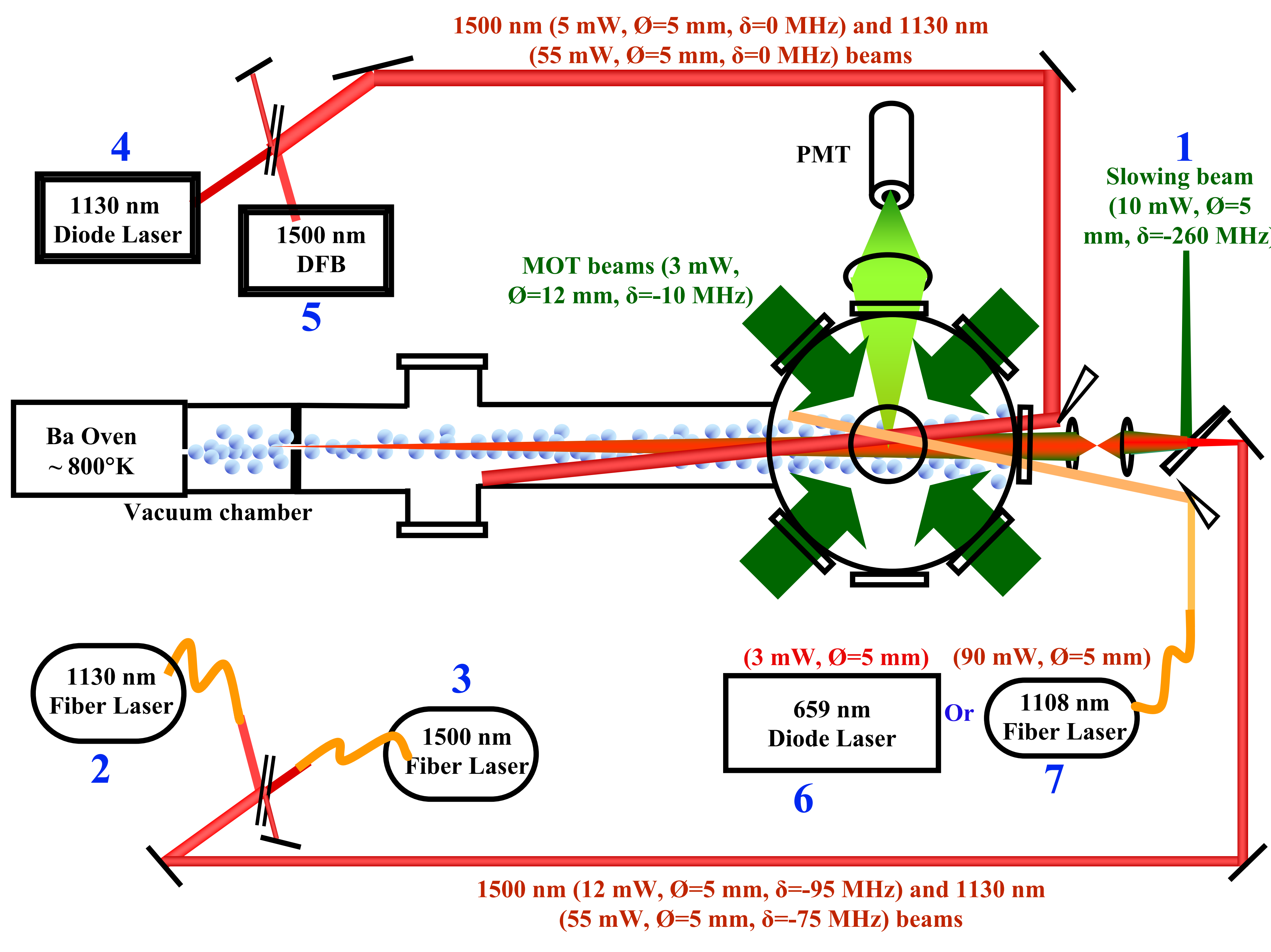
Deuteron edm
Marlene Silva
Klaas Brantjes

Atomic Physics

Gabriel Hasan
Ronnie Hoekstra
Albert Mollema

Theory

Rob Timmermans
Lotje Wansbeek



1500 nm (5 mW, Ø=5 mm, δ=0 MHz) and 1130 nm
(55 mW, Ø=5 mm, δ=0 MHz) beams
4
1130 nm
Diode Laser
1500 nm
DFB
5
PMT
1
Slowing beam
(10 mW, Ø=5
mm, δ=-260 MHz)
MOT beams (3 mW,
Ø=12 mm, δ=-10 MHz)
Ba Oven
~ 800°K
Vacuum chamber
1130 nm
Fiber Laser
2
3
1500 nm
Fiber Laser
(3 mW, Ø=5 mm)
(90 mW, Ø=5 mm)
659 nm
Diode Laser
Or
1108 nm
Fiber Laser
6
7
1500 nm (12 mW, Ø=5 mm, δ=-95 MHz) and 1130 nm
(55 mW, Ø=5 mm, δ=-75 MHz) beams